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Ferromagnetic Resonance On Metallic Glass Ribbons

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ABSTRACT

Ferromagnetic resonance data on metallic glasses, at room temperature, in X band, are discussed. The spectra were decomposed into two Lorentzian lines and the angular dependence of their main parameters (line width and position) is fully analyzed. It is proved that the usual approaches are not able to describe accurately the experimental data. This behavior is ascribed to the misalignment of the magnetization with respect to the external magnetic field, and successfully tested by using a "relaxed" resonance condition that allows a small misalignment of the magnetization relative to the external magnetic field.

INTRODUCTION

Metallic glasses are available as ribbons produced by rapid quenching from the melt. They exhibit both metallic and soft magnetic features and present high mechanical strength and hardness. Striped domain morphology is obtained [1] by annealing the metallic glass in external magnetic fields, confined within the plane of the ribbon. Magnetostrictive transducers are produced from metallic glasses, as the magnetomechanical coupling is usually large. Under the effect of the external magnetic field, the domain wall motion has a negligible contribution to the reorientation of the magnetization in an external magnetic field [1]. The free energy of a magnetic material, of unit volume, is [2]:

$$F = -\vec{M}\vec{H} + K_1(\alpha_1^2\alpha_2^2 + \alpha_1^2\alpha_3^2 + \alpha_2^2\alpha_3^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) + \alpha_1^2K_1^U + \alpha_1^4K_2^U + \\ + (N_XM_X^2 + N_YM_Y^2 + N_ZM_Z^2) + E'(\lambda, \sigma, NM^2) \quad (1)$$

The terms occurring in this equation are associated with (in the order of appearance) are: The Zeeman energy, the first and second order cubic magnetocrystalline anisotropy, the first and second order uniaxial anisotropy, the demagnetizing effects, the magnetostriction and higher order contributions. M is the magnetization, H the intensity of the applied magnetic field, K_1 and K_2 the cubic magnetocrystalline anisotropy constants, K_1^U and K_2^U the uniaxial magnetocrystalline anisotropy constants, and α_i (i =1,2,3) the direction cosines of the magnetization with respect to the coordinate axes. In the derivation of (1), only the diagonal components of the demagnetizing tensor **N** ($N_{jj} = N_j$ where j = X, Y, Z) were considered. The last term, E', depends on the magnetostriction constants λ, stresses σ demagnetizing factor N and on the direction of the magnetization, M. It was introduced to take into consideration stress and magnetostriction effects. The position of the ferromagnetic resonance line is given by [2, 3]:

$$\left(\frac{\omega}{\gamma}\right)^2 = H_{eff}^2 = \frac{(1+\varepsilon^2)^{1/2}}{M^2 \sin^2\theta_0}\left[\left(\frac{\partial^2 F}{\partial\theta^2}\right)\left(\frac{\partial^2 F}{\partial\varphi^2}\right) - \left(\frac{\partial^2 F}{\partial\theta\partial\varphi}\right)^2\right] \quad (2)$$

$$\left(\frac{\partial F}{\partial\theta}\right)_{\theta=\theta_0} = 0 \qquad \left(\frac{\partial F}{\partial\varphi}\right)_{\varphi=\varphi_0} = 0 \quad (3)$$

The derivatives of the free energy are estimated at equilibrium ($\theta=\theta_0$, $\varphi=\varphi_0$). The damping associated with the time evolution of the magnetization in an external magnetic field is introduced by ε. Within the thermodynamic approach, the peak-to-peak line width of the ferromagnetic resonance spectrum, H_{PP} is [2]:

$$H_{pp} \propto \Delta H = \frac{\varepsilon\gamma}{M}\frac{1}{\left(\frac{d\omega}{dH}\right)}\left[\left(\frac{\partial^2 F}{\partial\theta^2}\right) + \frac{1}{\sin^2\theta_0}\left(\frac{\partial^2 F}{\partial\phi^2}\right)\right] \quad (4)$$

EXPERIMENTAL

Ferromagnetic resonance (FMR) investigations on some amorphous magnetic ribbons ($Fe_{40}Ni_{38}Mo_4B_{18}$-2826 MB, $Fe_{78}B_{13}Si_9$-2605 TCA and $Fe_{66}Co_{18}B_{15}Si$-2826 CO) have been performed using a JES-ME-3X spectrometer, operating in the X band (≈ 9 GHz).

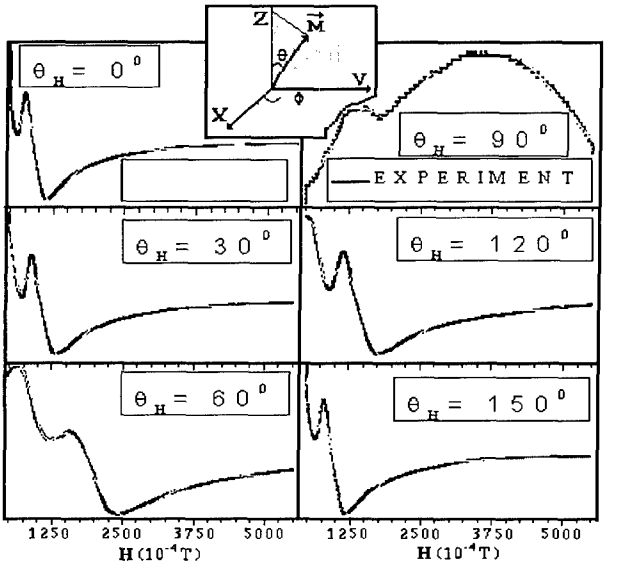

Figure 1. The FMR spectra of METGLASS 2605 TCA at different orientations.

The angular dependence of the resonance lines, for an out of plane configuration (i.e. the static external field is normal to the plane of the ribbon-see the inset of Figure 1), at room temperature, was investigated in detail. The FMR spectrum of the amorphous magnetic ribbons (which is in fact the derivative of the absorption line [2, 5]) has been successfully deconvoluted into two Lorentzian lines, for any composition and most orientations of the magnetic ribbon relative to the external magnetic field (see Figure 1), using the relation [5]:

$$I(X) = \frac{32I^{(1)}\dfrac{(H - H_{res}^{(1)})}{H_{PP}^{(1)}}}{\{3 + 4[\dfrac{(H - H_{res}^{(1)})}{H_{PP}^{(1)}}]^2\}^2} + \frac{32I^{(2)}\dfrac{(H - H_{res}^{(2)})}{H_{PP}^{(2)}}}{\{3 + 4[\dfrac{(H - H_{res}^{(2)})}{H_{PP}^{(2)}}]^2\}^2} + P_1 + P_2 H \qquad (5)$$

Where $H_{res}^{(1)}$ and $H_{res}^{(2)}$ are the resonance field for the low and high field components, $I^{(1)}$ and $I^{(2)}$ are the components of the resonance line amplitude for the low and high field components, $H_{PP}^{(1)}$ and $H_{PP}^{(2)}$ are the resonance line width for the low and high field components, respectively. The parameters P_1 and P_2 allow for a linear base line correction. The possibility to decompose the resonance spectrum into symmetric Lorentzian lines indicates that the contribution of skin effects is negligible.

The position and width of the high field resonance line is sensitive to the orientation of the film relative to the external magnetic field. The low field resonance line position, $H_{res}^{(1)}$ cannot be recorded for all orientations, as it occurs at very small magnetic fields. However, the deconvolution allows, at most orientations, an accurate estimation of the resonance line parameters for both lines. The resonance line position was noticed at the lowest magnetic field if the external magnetic field is parallel to the plane of the sample. As may be observed from Figure 1, starting to rotate the sample, from this orientation, the resonance field position is increased until a maximum is reached in the perpendicular configuration (external field normal to the plane of the sample). In this case, the resonance line position is given by [2, 4]:

$$H_{eff}^2 = H^2 + H(4\pi M_S + 2H_{K1} - 2H_{K2}) + H_{K1}(4\pi M_S + H_{K1} - H_{K2}) \qquad (6)$$

As the FMR studies on metallic glasses concern materials with a magnetocrystalline anisotropy smaller by 2 orders of magnitude than the demagnetizing effects [4], taking into account that $g \approx 2.0$, it is possible to have an estimation of $4\pi M_s$ by neglecting the contribution of these terms. The values of $4\pi M_s$, associated with the high field line are: 2.13 T (2605 TCA), 6.53 T (2826 CO) and 2.07 T (2826 MB). These values are of the correct order of magnitude, with the exception of sample 2826 CO. The same calculus for the low field lines result in 1.1 T (2605 TCA), 1.09 T (2826 CO) and 1.08 T (2826 MB). The following relation gives the resonance line position for the parallel configuration:

$$H_{eff} = H - 4\pi M_S + H_{K2} - (1/2)H_{K1} \qquad (7)$$

Neglecting the contribution of the magnetocrystalline anisotropy the estimated values of $4\pi M_S$ associated with the high field lines, are 0.095 T (2605 TCA), 0.19 T (2826 CO) and 0.12 T (2826 MB). The value of the resonance field corresponding to the low field line cannot be

described by the expressions (6) and (7), whereas for the high field line a qualitative agreement is met for the parallel configuration (excepting the 2605 SC1 sample). The low field resonance cannot be considered as an AFMR line as neither the phase of the resonance line, nor the position is consistent with this hypothesis [4]. The strongest deviation from the theoretical expectations is noticed when the sample is perpendicular on the magnetic field. It was concluded that the deviation of the magnetization from the direction of the external magnetic field is stronger in the perpendicular configuration, due to the shape anisotropy. Under these circumstances, the underlying approximations used to derive the relations (6) and (7) are not fulfilled. From the physical point of view, this implies that the sample is not fully saturated, at the resonance field. In order to test this hypothesis, an expression for the angular dependence of the resonance line, supposing a small misalignment of the magnetization along the external magnetic field, was derived.

$$H_{1,2} = -[2H_{K,2}(3\sin^2\theta_H\cos^2\theta_H - \cos^4\theta_H) + M(N_\perp - N_K)\cos 2\theta_H] \pm$$
$$\pm\{[2H_{K,2}(3\sin^2\theta_H\cos^2\theta_H - \cos^4\theta_H) + M(N_\perp - N_K)\cos 2\theta_H]^2 + \lambda H_{eff}^2\}^{1/2} = 0 \quad (8)$$

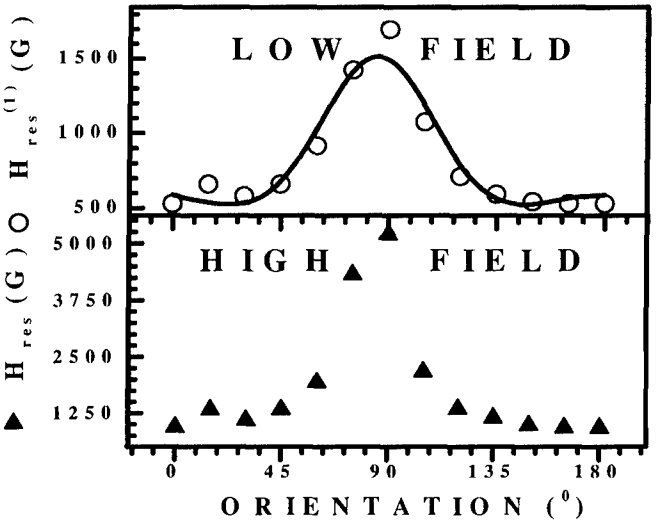

Figure 2. The angular dependence of the resonance line position, for the sample 2605 TCA.

Where λ is a constant of the order $\sin\theta/\sin\theta_H$ that allows an estimation of the magnetization misalignment, θ is the orientation of the magnetization with respect to the OZ axis and θ_H is the orientation of the external magnetic field with respect to the same axis. Actually, only θ_H is known and θ may be estimated by using an appropriate model. The resonance line position was

derived supposing an uniaxial magnetocrystalline field and the corresponding H_{K1} term has been absorbed in the parallel demagnetizing term $N_{\|}=N_K-H_{K1}/4\pi M_S$.

The best fit obtained using the relation (9) is represented by thick curves in Figure (2). Although the agreement is good, the largest deviation between the prediction based on equation (9) and the experimental data is noticed when the external magnetic field is perpendicular on the ribbon. That indicates that although a significant improvement was obtained, the misalignment of the magnetization with respect to the external magnetic field, in this configuration, is not very small. Neglected the effect of mosaicity, the angular dependence of the resonance line width is roughly identical with the angular dependence of the resonance line position, up to a multiplicative constant, that is equal to the dampening of the magnetization, ε. As may be observed, from Figure 3, such dependence is qualitatively supported by the experimental data. The largest deviation is noticed in the perpendicular configuration and may be due to the fact that this oversimplified picture assumed that the dampening of the magnetization is independent on the misalignment between the external magnetic field and the magnetization of the sample. The damping constants are, up to the same multiplicative factor equal to 0.429 (2605 TCA), 0.503 (2826 MB) and 0.765 (2826 CO).

The origin of the second line is not obvious. In ferromagnetic experiments, two or more solutions are possible and therefore, several resonance lines may be observed. The possibility of a stripe structure of magnetic domains, the mosaicity or the texture may also induce the split of the resonance line into several components. As this behavior is related to a dependence of the

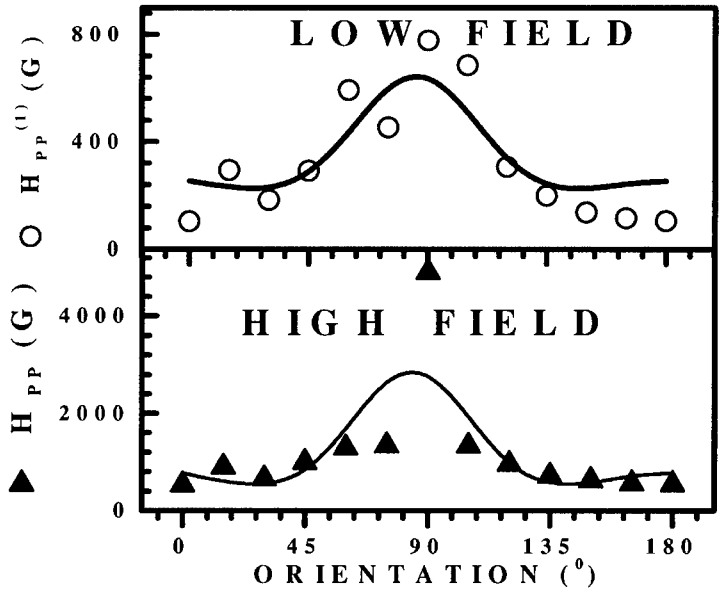

Figure 3. The angular dependence of the resonance line width, for the sample 2605 TCA

ferromagnetic resonance spectra in a plane normal to the film, it seems reasonable to suppose that long spin waves with components normal to the film are excited. Two main mechanisms would induce a discontinuity in the shift of the resonance field, in the perpendicular configuration. The first is related to the impossibility of the magnetization to point along the external magnetic field. This behavior is due to the demagnetizing field and appears in not fully saturated samples. In magnetic wires and stripes, the magnetostatic interactions would shift also to infinity the resonance field in the perpendicular configuration (magnetic field normal on the wire). In the general case, although the enhancement of magnetostatic interaction reduces the coercive field, an increase of the saturation field is expected. This increase in the saturation field amplifies the contribution of the demagnetizing term and makes difficult the alignment of the magnetization along the external field, in the case in which the external magnetic field is normal on the ribbon [6].

DISCUSSIONS

Ferromagnetic resonance studies on magnetic glasses reveals the presence of at least two symmetric Lorentzian lines, and indicates the absence of skin effect. The angular dependence of the resonance line reflects that the magnetization is not perfectly along the external magnetic field, mainly if the external magnetization is normal to the plane of the film. This is due to the demagnetizing field. An expression for the angular dependence of the resonance field, supposing a small misalignment of the magnetization relative to the external magnetic field was proposed and successfully tested. The large value estimated for this misalignment of the magnetization suggests a supplementary contribution due to stripe like structure of the sample with magnetostatic interactions among these stripes. From the angular dependence of the resonance line width, the dampening constant is estimated. However, the correlation between the predictions and the experimental results is only qualitative as in order to avoid calculus complications it was supposed that the dampening constant is independent on the magnetization misalignment.

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